



Wire Coatings

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16.1. REASONS FOR COATING WIRE

In many applications wire is often, or nearly always, used with a coating. This is done because of the need for electrical insulation and corrosion protection. Other important motivations include the need to provide a superior surface for lubrication and to facilitate bonding to other structural media, such as the role of a brass coating in bonding steel to rubber.

This chapter reviews the rudiments of important coating technologies, where such coatings are a prominent feature of wire in a semi-finished product form. This chapter will not, however, review coatings that play transient roles in wire processing, such as lubricants, lubricant carriers, cleaners, and temporary corrosion inhibitors. Aspects of these latter coatings are discussed in Chapters 8 and 17.



16.2. COATING TYPES AND COATING PROCESSES

Coatings for electrical insulation include *enamels* and *polymers* of many types. Coatings for corrosion protection include *metals* such as zinc and

aluminum, as well as polymers. Lubrication and bonding may be facilitated with copper and copper alloys. Paper wrapping also serves a useful purpose.

Major coating technologies include enameling, extrusion, hot dipping, electro-coating, electro-less coating, cladding, and wrapping.



16.3. ENAMELS AND ENAMELING

16.3.1 General logistics

Enamels are most prominently associated with copper and aluminum magnet wire. These smooth, thin insulators minimize space consumed in wound coils, have high dielectric strength, and may provide moisture and solvent resistance.

A coating of enamel, in a resinous solution, is applied to the wire, and the wire passes through a die so as to leave a film coating on the wire. This initial coating is dried and cured, and the process is repeated as many as six times. Figure 8.21 reveals these coatings in cross section. The coatings may involve more than one enamel formulation. Overall increase in wire diameter attributable to the layers of enamel is called the *build*. Build specifications may be described as “single,” “heavy,” and “triple,” where a heavy build is twice the thickness of a single build, and a triple build is three times the thickness of a single build.

Facilities for enameling are called enameling “towers,” because of the vertical layout of drying and curing operations. Enameling towers may be in tandem with drawing, annealing, and cleaning operations.

16.3.2 Types of enamels

A practical listing and general discussion of major magnet wire enamels or dielectrics is presented in the *Electrical Wire Handbook*.¹¹⁸ Enamels may be used in combination, and numerous variations exist. A brief listing follows:

Plain enamel. Synthetic resins and modifying agents. Applications include transformer and telephone coils.

Nylon. A tough thermoplastic that may be removed by molten solder. Applications include automotive electrical devices.

Polyurethane. Formed by reacting a form of isocyanate and a polyester. May be removed with molten solder. Used in fine wire applications.

Polyvinyl formal (Formvar). Classical enamel (see Figure 8.21), involving a reaction with phenolformaldehyde and possibly with

isocyanate and melamine. Requires stress relief. Is still used where resistance to oil may be required.

Solderable acrylic. Water dispersion of acrylonitrile polymer, acrylic acid, and butyl acrylate is applied. May be removed by molten solder. Applications include automotive electrical devices.

Epoxy. Early resin solution coatings had properties similar to those of polyvinyl formal. Powder coating technologies have subsequently become available. Provides good resistance to oil containing media.

Polyester. This enamel is from the terephthalic acid category. Good heat and heat shock resistance. Used in a variety of electrical and electrical coil products.

Polyimide. Involves the reaction of pyromellitic dianhydride with an aromatic diamine. Very high thermal stability and overload resistance. Resistant to solvents and acids, but not to alkalis. Used in high performance electrical devices.

Polyester-polyamide-imide. The base is a modified polyester with an overcoat of amide-imide polymer. Superior properties and wide general application.



16.4. EXTRUSION

16.4.1 General logistics

In the polymer extrusion process (not to be confused with metal deformation processing, such as aluminum extrusion), a thermoplastic polymer in particulate form is fed into a hopper, and it flows into a screw-containing barrel. The action of the screw drives the powder ahead, achieving melting and pressurization of the polymer. [Figure 16.1](#) provides a schematic illustration of a typical screw extruder.¹¹⁹ For wire coating applications, the pressurized, molten polymer is forced into a crosshead where it surrounds heated wire stock, which then becomes coated as it passes through the crosshead and out a die. A schematic illustration of the crosshead is displayed in [Figure 16.2](#).¹²⁰

16.4.2 Polymer coatings

A practical listing and general discussion of major polymers for wire coating can be found in the *Ferrous Wire Handbook*.¹²¹ A brief listing follows.

Softened polyvinyl chloride (PVC). Since PVC can be hard and brittle at ambient temperature, softeners, such as esters, are added for wire

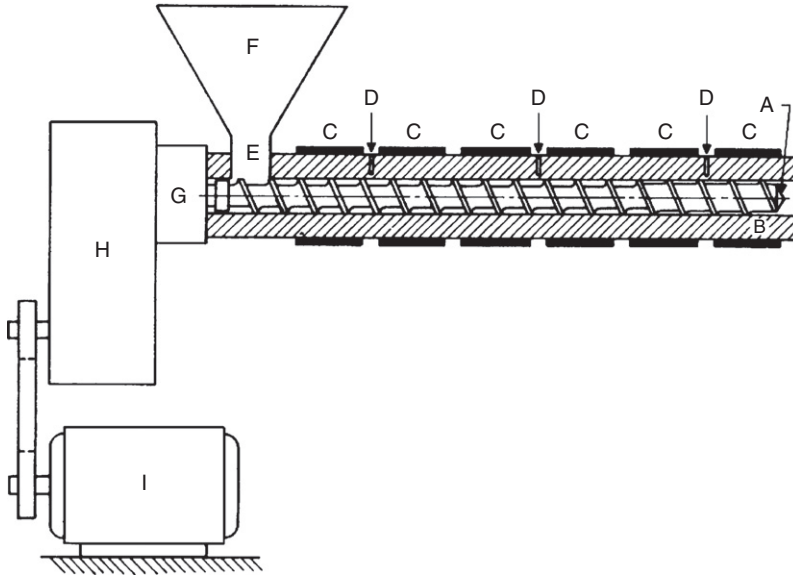


Figure 16.1 Schematic drawing of a polymer screw extruder: A, screw; B, barrel; C, heater; D, thermocouple; E, feed throat; F, hopper; G, thrust bearing; H, gear reducer; I, motor. From P. N. Richardson, *Introduction to Extrusion*, Society of Plastics Engineers, Brookfield Center, CT, USA, 1974, 4. Copyright held by Society of Plastics Engineers, Brookfield Center, CT, USA.

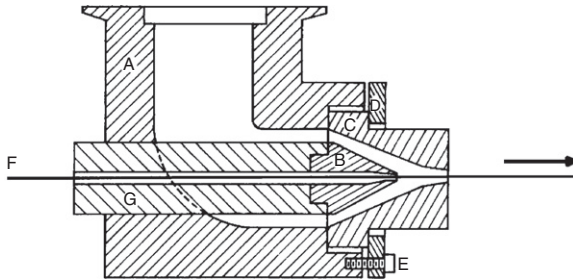


Figure 16.2 Schematic drawing of a wire-coating pressure die: A, die body, cross head; B, guider tip; C, die; D, die retaining ring; E, die retaining bolt; F, wire; G, core tube. From P. N. Richardson, *Introduction to Extrusion*, Society of Plastics Engineers, Brookfield Center, CT, USA, 1974, 84. Copyright held by Society of Plastics Engineers, Brookfield Center, CT, USA.

coating applications. Stabilizing compounds and filler material may be added to the softened PVC. Polyvinyl chloride is a good electrical insulator.

Polyamide plastics, such as nylon. Provides high strength and toughness.

Polyethylene. Highly resistant to solvents, water, and many caustic salt solutions and organic acids.

Polypropylene. Strength, toughness, and chemical resistance are generally greater than for polyethylene, but polypropylene is vulnerable to daylight exposure.

Polycarbonate. Strength, toughness, and chemical resistance are generally high, but polycarbonate is vulnerable to alkaline media, amines, and ammonia solutions.

Extrudable polyfluorocarbons. Some major polyfluorocarbons, including Teflon[®] are not extrudable; however, family members such as polyfluorochloroethylene are. These compounds have strong resistance to essentially all acids and alkalis. Extrudable polyfluorocarbons are less stable at elevated temperature than Teflon[®].



16.5. HOT DIPPING

With this technology, a coating is achieved by passing the wire through a bath of molten coating material. Upon emerging from the bath, the wire is passed through a wiping member that trims the coating to a desired thickness. The role of the wiping process is somewhat analogous to that of the enameling die cited earlier. The dip coating procedure may be preceded by a thermal treatment, by pickling and cleaning, and by application of a flux. It may be followed by annealing, quenching, and supplemental coating. In some cases, a metallurgical reaction between the coating and the substrate is brought about by the hot dipping action or a subsequent anneal. A prominent example is galvannealing, where intermetallic compounds of iron and zinc are formed between the zinc and the iron. Supplemental coatings may include waxes, polymers, and dichromates (where permissible). A schematic illustration of a hot-dip coating line is presented in [Figure 16.3](#).¹²²

Hot dipping technology has been widely applied to the coating of steel with zinc (hot-dip galvanizing), and practices have been developed for zinc alloys, such as Zn-Al and Zn-Al-Sn. Aluminum may be applied by hot dipping. Zinc and aluminum coatings are generally for corrosion resistance, and the coating acts as a sacrificial anode relative to the steel substrate. Tin may be applied to steel or copper with hot-dip technology.



16.6. ELECTRO-COATING

In this technology, the wire, as a cathode, is exposed to an electrolyte containing cations of a coating metal. The cations of the coating metal are

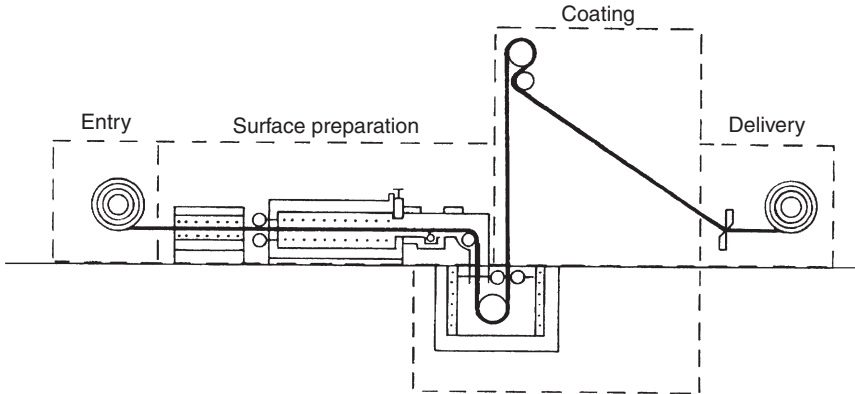


Figure 16.3 Illustration of a classic hot-dip coating line. From A. R. Cook, *Galvanized Steel, Encyclopedia of Materials Science and Engineering, Vol. 3*, M. B. Bever, editor-in-chief, Pergamon Press, Oxford, UK, 1986, 1899. Copyright held by Elsevier Limited, Oxford, UK.

reduced to the coating metal at the cathode. The coating ions may enter the electrolyte at the anode. Electroplating is a versatile technology, applicable to many systems. Common plating materials include zinc, chromium, nickel, cadmium, copper, tin, aluminum, and various noble metals (gold, silver, platinum, etc.).

In the classic example of electrogalvanizing, a zinc anode is the source of zinc ions that migrate to the steel wire cathode, where they are reduced to metallic zinc. In principle, the process can be used on any steel, and little reaction occurs between the zinc and the iron.

Tire cord wire is electroplated with brass to facilitate adhesion of the steel wire to rubber. In one such technology, referred to as *diffusionless*, brass is plated from an electrolyte (typically sodium cyanide solution) containing both copper and zinc cations. An alternate technology is *thermodiffusion*, where copper is electroplated followed by zinc. A subsequent thermal treatment allows the copper and zinc to interdiffuse en route to the brass alloy.

Tire bead wire may be electroplated with bronze using diffusionless technology. A stannate-cyanide bath is used with a few percent tin plating together with copper.

Further applications include copper on aluminum in electrical assemblies, tin plating of copper to ease soldering, precious metal plating of electronic circuit materials (to avoid oxidation and increased contact resistance), and various coatings for aesthetic purposes.



16.7. OTHER COATING TECHNOLOGIES

Apart from enameling and extrusion, polymer coatings may be applied by *fluidized bed* technology and *immersion*. In the fluidized bed approach, heated wire is passed through powdered plastic that is “fluidized” with gas flow. The plastic powder melts on contact with the heated wire, creating a coating of appropriate thickness with proper process design and control. Immersion technology may be subdivided into *hot* and *cold* processes. In the hot approach, a heated wire is immersed in a plastic paste, which forms the desired coating. In the cold approach, the wire is not heated before immersion in a plastic paste. However, the plastic must be cured in a subsequent thermal treatment.

In some applications magnet wire is wrapped with paper or tape insulation. Glass fibers and polyester-glass “yarns” also may be applied by wrapping.

Metal coating or cladding may be physically applied to a wire substrate and then drawn as a composite. For example, a rod may be placed in a tube, and then the two-piece assembly may be drawn or extruded. Analogous techniques involve casting of the coating metal on a rod or billet substrate and hot-isostatically pressing coating metal (e.g., powder) on a rod or billet substrate.

Coating applications involving spraying and vapor deposition also have been developed.



16.8. ZINC ALLOY COATING OF STEEL – A DETAILED ILLUSTRATION AND ANALYSIS¹²³

A zinc-5% aluminum alloy may be usefully applied to a steel substrate by way of the Galfan[®] process. A double-dip Galfan[®] line is schematically illustrated in [Figure 16.4](#). In the double-dip method, the first dip involves a conventional hot-dip galvanization process, followed by a second hot-dip in the Zn-5%Al alloy. This double-dip approach is necessary because of the incompatibility of Zn-5%Al with many flux systems.

The galvanized coating acquired in the first dip generally forms a sequence of intermetallic iron-zinc compounds between the iron substrate and an outside layer of nearly pure zinc. The intermetallic compounds are embrittling. However, upon passage through the hot Galfan[®] bath, the coating from the prior bath is transformed into an aluminum-iron-zinc intermetallic compound. The final coating involves a layer of Galfan[®] alloy on top of the layer of Al-Fe-Zn intermetallic compound.

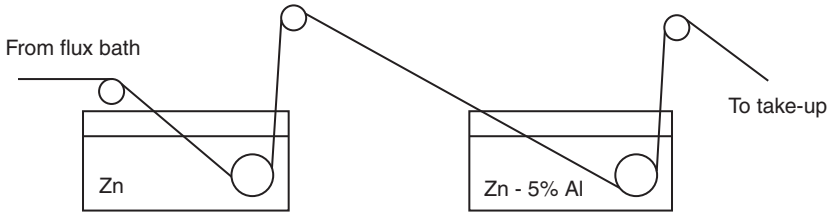


Figure 16.4 Schematic illustration of a double-dip Galvannealing line. From F. E. Goodwin and R. N. Wright, *The Process Metallurgy of Zinc-Coated Steel Wire and Galvannealing Bath Management*, Conference Proceedings, Wire & Cable Technical Symposium, 71st Annual Convention, The Wire Association International, Inc., Guilford, CT, 2001, 135.

The aluminum that enters the Al-Fe-Zn intermetallic depletes the aluminum composition of the Galvannealing alloy bath, thus requiring careful monitoring and management of this bath. The following model of Galvannealing bath aluminum concentration is useful for bath management.

If the process line is able to add Galvannealing alloy to keep the bath mass constant, then the incremental depletion of aluminum associated with the increment of wire coating can be expressed as:

$$M (dC_{Al}) = -M_{Al} (dA) + (0.05) M_G (dA) - C_{Al} M_{Go} (dA), \quad (16.1)$$

where C_{Al} is the aluminum concentration in the bath, dC_{Al} is the incremental change in aluminum bath concentration, dA is the increment of wire surface coated, M is the mass of the bath, M_{Al} is the mass of aluminum per unit of wire surface area in the transformed intermetallic layer, M_G is the net mass of Galvannealing alloy melt removed per unit of wire surface area, and M_{Go} is the mass of the Galvannealing alloy overlay that solidifies per unit of wire surface area.

The left-hand side of Equation 16.1 is the incremental mass of aluminum lost when an increment of wire surface area is coated in the Galvannealing alloy bath. There are three contributions to the incremental mass, specifically the three terms on the right side of Equation 16.1. The first term is the mass of aluminum lost to the intermetallic layer. The second term is the amount of aluminum added to the bath from the replenishment process. The third term is the amount of aluminum lost due to solidification of the bath alloy on the wire.

Equation 16.1 can be reorganized and integrated to yield Equation 16.2.

$$C_1 = (Z + C_0) \exp(-YA) - Z \quad (16.2)$$

where C_0 is the concentration of aluminum in the starting bath, C_1 is the concentration of aluminum in the bath after coating a surface area of A , Y is (M_{G0}/M) , and Z is $[1 - (0.05) M_G]/M_{G0}$.

Using Equation 16.2 and the practical values of descriptors and parameters involved, bath maintenance practices can be planned. The general approach would be to associate a rate of Galfan[®] alloy bath replenishment with a rate of supplemental aluminum addition. Periodic bath analysis should be undertaken. Monitoring of bath replacement needs can provide improved estimates of M_G , the galvanized coating weight, and the overall coating weight. The value of M_{G0} can be estimated as 20 g/mm² less than the overall coating rate. With process experience and observations, increasingly sophisticated bath management practices will evolve.



16.9. COMPOSITE MECHANICAL PROPERTIES OF COATED WIRE

In many cases strength and ductility specifications for coated wire are based on measurements of the bare wire. While this may suffice in an empirical way for certain commercial quality purposes, bare wire mechanical properties vary considerably from those of the composite, coated wire. This is especially the case where bending and twisting are involved, since these deformation modes develop maximum strain at the composite wire surface where coating properties may dominate. The contribution of the coating to composite mechanical properties is also substantial in tensile deformation, as illustrated by the work of Wright and Patenaude.¹²⁴

Wright and Patenaude conducted tests on PVC insulated, 8 AWG copper wire, revealing the respective contributions of the PVC coating and the core wire to strength in tension and to elongation. The presence of the PVC jacket was observed to forestall necking and increase tensile elongation when the composite was compared to the copper. The tensile properties measured for the copper are illustrated in Figure 16.5, and those for the PVC alone are seen in Figure 16.6. Tensile test results for the composite, coated conductor are shown in Figure 16.7. In these tests, stress-strain relations after necking or at high strains must be interpolated between the initial portion of the stress-strain curve and values measurable at necking or fracture. In any case, it is clear that the composite conductor has higher uniform elongation and fracture strain than the copper on a stand-alone basis.

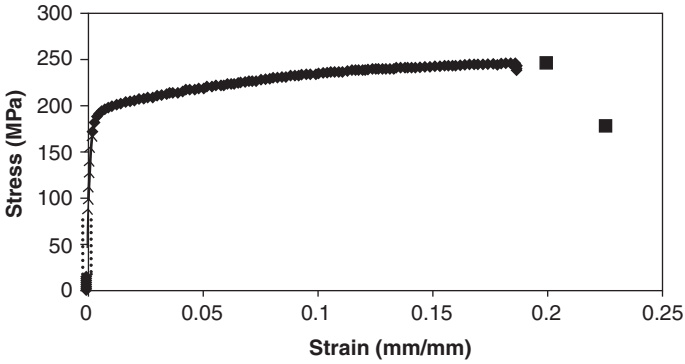


Figure 16.5 Engineering stress-strain curve for copper removed from its PVC insulation. From R. N. Wright and K. Patenaude, *Wire Journal International*, 34(5) (2001) 94.

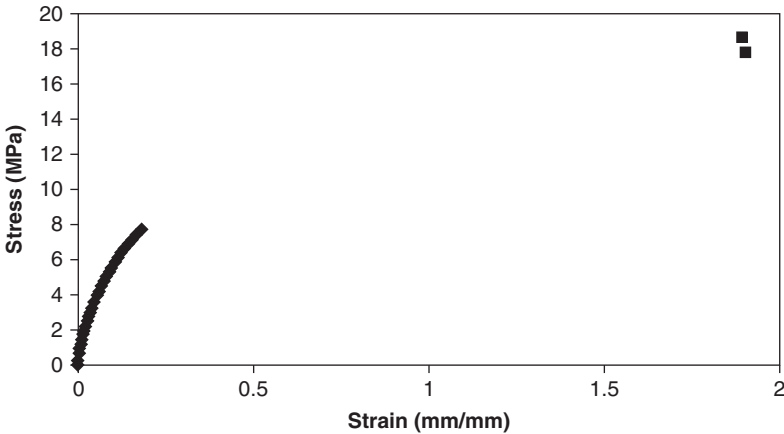


Figure 16.6 Engineering stress-strain curve for PVC insulation removed from copper wire. From R. N. Wright and K. Patenaude, *Wire Journal International*, 34(5) (2001) 94.

The strength of the composite, in tension, is less than that of the copper on a stand-alone basis. The simplest projection of composite properties in tension is the “rule of mixtures,” as per:

$$\sigma_{\alpha+\beta} = \sigma_{\alpha} (A_{\alpha}/A) + \sigma_{\beta} (A_{\beta}/A), \tag{16.3}$$

where $\sigma_{\alpha+\beta}$ is the strength of the composite, or α and β , in tension; σ_{α} is the strength of component α ; σ_{β} is the strength of component β ;

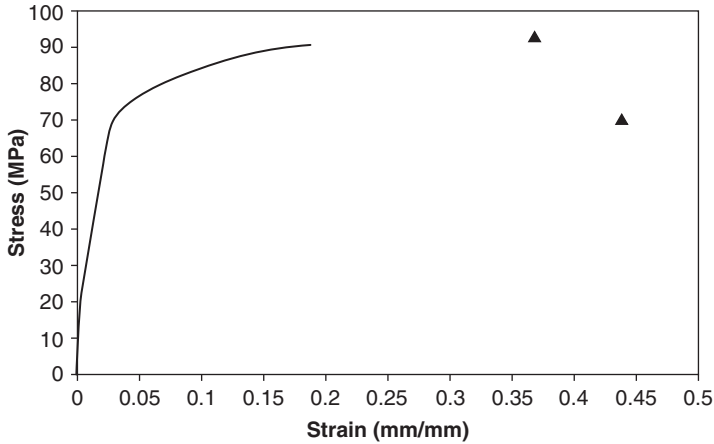


Figure 16.7 Engineering stress-strain curve for PVC insulated 8 AWG copper conductor. From R. N. Wright and K. Patenaude, *Wire Journal International*, 34(5) (2001) 94.

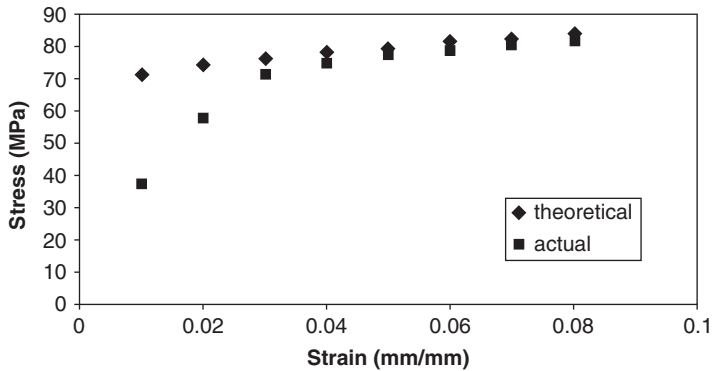


Figure 16.8 A comparison of the theoretical rule of mixtures projection with data from Figure 16.7. From R. N. Wright and K. Patenaude, *Wire Journal International*, 34(5) (2001) 94.

(A_{α}/A) is the cross-sectional area fraction of α ; and (A_{β}/A) is the cross-sectional area fraction of β . A rule of mixtures projection from the data of Figures 16.5 and 16.6 is compared with the composite data of Figure 16.7 in Figure 16.8. Equation 16.3 is consistent with the actual composite tensile data at strains beyond 0.03 to 0.04 (3–4%). Below this strain range, the rule of mixtures overestimates the strength of the composite. It is hypothesized that this discrepancy is related to the low interfacial strength between the copper and the PVC.



16.10. QUESTIONS AND PROBLEMS

16.9.1 Equation 16.1 involves three components of the incremental mass of aluminum lost (or gained) when an increment of surface area is coated in the Galfan[®] process. Reviewing Figure 16.4, make certain that you understand the aluminum transfer involved with the three components. Using a sketch of Figure 16.4 and arrows, make a diagram of the transfers of aluminum.

Answer: The first term involves a transfer of aluminum into the iron-zinc coating that was established in the zinc bath. This first term aluminum transfer actually occurs in the second, Zn-5%Al bath. The second term involves aluminum directly added to the Zn-5%Al bath. The third term involves aluminum lost as the Zn-5%Al bath alloy solidifies on the wire.

16.9.2 Consider Figures 16.5 and 16.7. What are the implications of the coating contribution to tensile properties for applications that involve winding under tension?

Answer: The coated, composite conductor yields at a significantly lower stress than copper by itself (70 vs. 180 MPa). On the other hand, the coated, composite conductor may be elongated considerably more than the copper alone (strains of 0.35 vs. 0.18).